Names, Bindings, and Scope

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Chapter 5 Topics

- Introduction
- Names
- Variables
- The Concept of Binding
- Scope
- Scope and Lifetime
- Referencing Environments
- Named Constants

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Introduction

- Imperative languages are abstractions of von Neumann architecture
  - Memory
  - Processor
- Variables are abstractions of memory cells in Memory.

- Memory is byte-addressable. A variable-sized integer may use several cells.

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Introduction

- Imperative languages are abstractions of von Neumann architecture
  - Memory
  - Processor
- Fundamental elements in terms of variable design include:
  - type, scope, lifetime, type checking, and initialization

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Names or identifiers

- Design issues for names:
  - Are names case sensitive?
  - Are special words reserved words or keywords?

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Names (continued)

- Length
  - If too short, they cannot be connotative
  - Language examples:
    - C99: no limit, but only the first 63 are significant; also, external names are limited to a maximum of 31
    - C89: limit, you need to declare variables at the beginning, not things like for (int i=0; i<5; i++)
    - C# and Java: no limit, and all are significant
    - C++: no limit, but implementers often impose one

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Names (continued)

- Special characters
  - PHP: all variable names must begin with dollar signs
  - Perl: all variable names begin with special characters, which specify the variable's type

```
$name = "Luis"; @colors = ("red", "green", "blue");
%ages = ("Alice" => 25,  "Bob"   => 30);
```

  - Ruby: variable names that begin with `@` are instance variables; those that begin with `@@` are class variables

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Names (continued)

- Case sensitivity
  - Disadvantage: readability (names that look alike are different)
    - Names in the C-based languages are case sensitive
    - Names in others are not: SQL, basic, COBOL, Pascal
    - Worse in C++, Java, and C# because predefined names are mixed case (e.g. `IndexOutOfBoundsException`)

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Names (continued)

- Special words
  - A *reserved word* is a special word that cannot be used as a user-defined name

```
int if = 5;
```

  - Potential problem with reserved words: If there are too many, many collisions occur (e.g., COBOL has 300 reserved words!)

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Variables

- A variable is an abstraction of a memory cell
- Variables can be characterized as a sextuple of attributes:
  - Name
  - Address
  - Value
  - Type
  - Lifetime
  - Scope

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Variables Attributes

- Name – not all variables have them
- Address – the memory address with which it is associated
  - A variable may have different addresses at different times during execution
  - A variable may have different addresses at different places in a program
  - If two variable names can be used to access the same memory location, they are called aliases
  - Aliases are created via pointers, reference variables, C and C++ unions
  - Aliases are harmful to readability (program readers must remember all of them)

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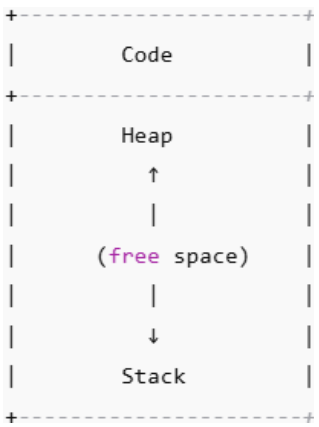
Variables Attributes (Examples)

Where is the variable x located?
User address space? r real address in RAM ?

```
void foo() {
   int x = 10;   // local variable
  }
```



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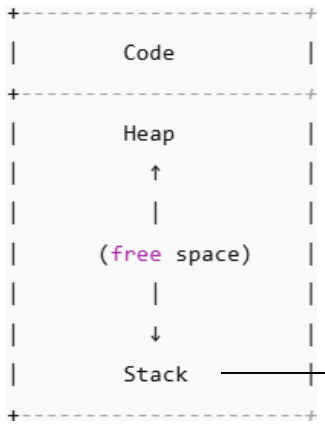
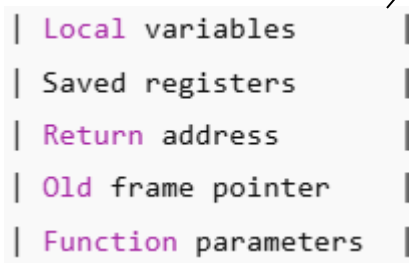
Variables Attributes (Examples)

Example

```
int main() {
    foo();
    foo();
    foo();
}
```



Stack frame



Running Stack
Concept of an evolving stack

Call 1 to foo():
Stack top → [x | return addr | old FP]

Return from foo():
Stack frame removed

Call 2 to foo():
Stack top → [x | return addr | old FP] ← may be at a different address (FP frame pointer)

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Variables Attributes (Aliases)

```
int main() {
    int x = 10;
    int *p = &x;   // p points to x
    int *q = &x;   // q ALSO points to x (alias)
    *p = 20;
    *q = 5; overwrites the same memory location.
}     // change x through p
```

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Variables Attributes (continued)

- *Type* – determines the range of values of variables and the set of operations that are defined for values of that type; in the case of floating point, type also determines the precision

- *Value* – the contents of the location with which the variable is associated

  - The l-value of a variable is its address
  - The r-value of a variable is its value

- *Abstract memory cell* – the physical cell or collection of cells associated with a variable

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The Concept of Binding

A *binding* is an association between an entity and an attribute, for instance:

Variable -> Type

Variable -> Value

Operation -> Symbol

- *Binding time* is the time at which a binding takes place.

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Possible Binding Times

- Language design time -- bind operator symbols to operations
  Example: * is bound to the multiplication operation at LDT

- Language implementation time-- bind floating point type to a representation

- Compile time -- bind a variable to a type in C or Java

```
gcc main.c -c
```

What happens here:

- Source code → object file (`.o`)
- Types are checked
- Syntax is checked
- Variables are assigned storage classes (static, automatic, etc.)
- Symbolic addresses/offsets are generated

But the program is **not running yet**.

- Load time -- bind a C or C++ `static` variable to a memory cell)

```
./program
```

Now the OS loader:

- Copies the program into memory
- Assigns real memory addresses to:
  - Code
  - Globals
  - Static variables
- Sets up stack and heap
- Applies relocations

Now variables have **real addresses in RAM**.

- Runtime -- bind a non-static local variable to a memory cell

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Static and Dynamic Binding

- A binding is *static* if it first occurs before run time and remains unchanged throughout program execution. (at compile time)
- A binding is *dynamic* if it first occurs during execution or can change during execution of the program

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Type Binding

- How is a type specified?
- When does the binding take place?
- If static, the type may be specified by either an explicit or an implicit declaration

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Explicit/Implicit Declaration (TYPE)

- An *explicit declaration* is a program statement used for declaring the types of variables
- int x = 10;
- float y = 3.14;

- An *implicit declaration* is a default mechanism for specifying the types of variables through default conventions, rather than declaration statements
- I = 10 X = 3.14 in FORTRAN, vars I–N are int, otherwise reals

- Basic, Perl, Ruby, JavaScript, and PHP provide implicit declarations
  - Advantage: writability (a minor convenience)
  - Disadvantage: reliability (less trouble with Perl)

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Explicit/Implicit Declaration (continued)

- Some languages use type inferencing to determine types of variables (context)
  - C# – a variable can be declared with **`var`** and an initial value. The initial value sets the type

```
var price = 19.99;      // double
```

  - Visual Basic 9.0+, ML, Haskell, and F# use type inferencing. The context of the appearance of a variable determines its type

```
Dim price = 19.95     ' Inferred as Double
```

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Dynamic Type Binding

- Dynamic Type Binding (JavaScript, Python, Ruby, PHP, and C# (limited)) Type checking happens at runtime
- Specified through an assignment statement
  e.g., JavaScript

```
list = [2, 4.33, 6, 8];
list = 17.3;
```

  - Advantage: flexibility (generic program units)
  - Disadvantages:
    - High cost (dynamic type checking and interpretation)
    - Type error detection by the compiler is difficult

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Variable Attributes (continued)

- Storage Bindings & Lifetime
  - Allocation – getting a cell from some pool of available cells
  - Deallocation – putting a cell back into the pool

- The lifetime of a variable is the time during which it is bound to a particular memory cell

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Categories of Variables by Lifetimes

- Static--bound to memory cells before execution begins and remains bound to the same memory cell throughout execution, e.g., C and C++ `static` variables in functions,
- Memory is reserved **before the program starts running**

  - Advantages: efficiency (direct addressing), history-sensitive subprogram support
  - Disadvantage: lack of flexibility (no recursion)

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Categories of Variables by Lifetimes

```
#include <stdio.h>
int counter = 0;   // static storage binding

void foo() {
   counter++;
   printf("counter = %d, address = %p\n", counter, (void*)&counter);
}
int main() {
   foo();
}
#include <stdio.h>
```

```
void foo() {
   static int x = 0;   // static storage binding
   x++;
   printf("x = %d, address = %p\n", x, (void*)&x);
}

int main() {
   foo();
}
```

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Categories of Variables by Lifetimes

- Stack-dynamic--Storage bindings are created for variables when their declaration statements are *elaborated*.

```
int main() {
  int x = 10;
}
```

  - Statically bound in type (The type of x is known and fixed at compile time Dynamically bound in storage)

Elaboration = **storage allocation + binding**

- If scalar, all attributes except address and value are statically bound
  - local variables in C subprograms (not declared **`static`**) and Java methods
- Advantage: allows recursion; conserves storage
- Disadvantages:
  - Overhead of allocation and deallocation
  - Subprograms cannot be history sensitive
  - Inefficient references (indirect addressing)

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Categories of Variables by Lifetimes

- *Explicit heap-dynamic* – int *p = malloc(sizeof(int)); *p = 10;
- Nameless, just a raw memory cell in the heap, *p is in the stack
- int *p; Pointer variable
- malloc(...) Heap memory cell

- Allocated and deallocated by explicit directives, specified by the programmer, which take effect during execution

- Referenced only through pointers or references, e.g. dynamic objects in C++ (via **`new`** and **`delete`**), all objects in Java
- Integer obj = new Integer(5); in java

- Advantage: provides for dynamic storage management
- Disadvantage: inefficient and unreliable

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Categories of Variables by Lifetimes

- *Implicit heap-dynamic*—variables whose memory is allocated on the heap automatically, without the programmer explicitly requesting it, and whose type may be determined at runtime.

- Allocation and deallocation caused by assignment statements
  - all variables in APL; all strings and arrays in Perl, JavaScript, and PHP. Example in Python

```
x = 10
y = "hello"
z = [1, 2, 3]
```

- Advantage: flexibility (generic code)
- Disadvantages:
  - Inefficient, because all attributes are dynamic
  - Loss of error detection

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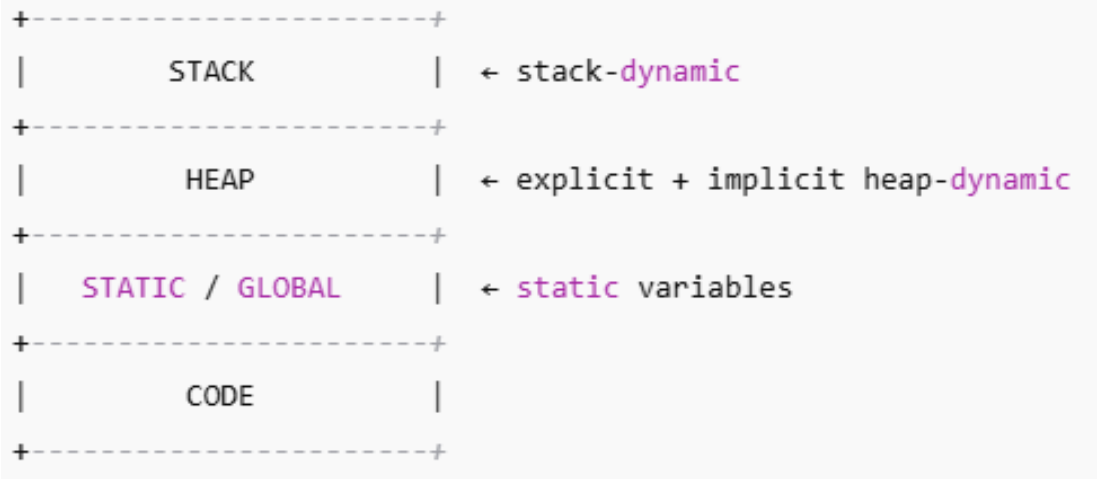
Visual process/variables



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Feature	Static	Stack-Dynamic	Explicit Heap-Dynamic	Implicit Heap-Dynamic
Where stored	Data segment	Runtime stack	Heap	Heap
When storage is bound	Before execution (load time)	At runtime when declaration is elaborated (function/block entered)	At runtime when programmer requests it	At runtime automatically when assigned
Who controls allocation	Compiler / loader	Runtime system (function call)	Programmer (`new`, `malloc`)	Language runtime / interpreter
Who controls deallocation	Automatic at program end	Automatic at function/block exit	Programmer (`free`, `delete`) or GC	Garbage collector / runtime
Lifetime	Entire program	Duration of function/block	Until explicitly freed (or GC)	Until no references remain
Can share storage between calls?	❌ No	✅ Yes (stack reused)	Sometimes (if freed and reused)	Managed automatically
Supports recursion?	❌ No (for locals)	✅ Yes	✅ Yes	✅ Yes
Memory efficiency	Low (always allocated)	High	Medium (depends on programmer)	Low–Medium (GC overhead)
Accessed how	Directly by name	Directly by name	Through pointers/references	Through references
Type binding	Static	Static	Static	Often dynamic
Examples of languages	FORTRAN (early), C globals	C, C++, Java locals	C (`malloc`), C++ (`new`)	Python, JavaScript, Ruby
Example code	`static int x;`	`int x;` inside function	`int *p = malloc(sizeof(int));`	`x = [1,2,3]` (Python)

Variable Attributes: Scope

- The *scope* of a variable is the range of statements over which it is visible
- The *local variables* of a program unit are those that are declared in that unit
- The *nonlocal variables* of a program unit are those that are visible in the unit but not declared there
- *Global variables* are a special category of nonlocal variables
- The scope rules of a language determine how references to names are associated with variables

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Static (lexical) Scope

- Based on program text
- To connect a name reference to a variable, you (or the compiler) must find the declaration
- *Search process*: search declarations, first locally, then in increasingly larger enclosing scopes, until one is found for the given name
- Enclosing static scopes (to a specific scope) are called its *static ancestors*; the nearest static ancestor is called a *static parent*
- Some languages allow nested subprogram definitions, which create nested static scopes (e.g., Ada, JavaScript, Common Lisp, Scheme, Fortran 2003+, F#, and Python)

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Static (lexical) Scope

```
function big() {

   function sub1() {
     var x = 7;
     sub2();
   }

   function sub2() {
      var y = x;
   }

  var x = 3;
  sub1();
}
```

What will be the value of y ?

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Perl offers dynamic scope option

```
------------------Perl --------
our $x = 10;
  sub foo {
      local $x = 20;   # dynamically scoped
      bar();
     }
   sub bar {
    print $x;  # prints 20
  }
------------------  shell script----

x=10
foo() {
  local x=20
  bar
}

bar() {
  echo $x   # prints 20
}
```

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Scope (continued)

- Variables can be hidden from a unit by having a "closer" variable with the same name

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Blocks

A **block** is a section of code that can contain **its own variable declarations** and therefore creates a **new static (lexical) scope** inside a larger scope.

Blocks in C and C-like Languages: statements inside { })

```
if (list[i] < list[j]) {
    int temp;
    temp = list[i];
    list[i] = list[j];
    list[j] = temp;
}
```

In Python, **blocks like if, for, or while do NOT create a new scope.**

```
if True:
    x = 10
print(x)   # still visible
```

Python does not use blocks to create new static scopes. Instead, functions define scopes each function introduces a new local scope, and nested functions create nested lexical scopes. Same with JavaScript

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The `LET` Construct

- Most functional languages include some form of `let` construct
- A let construct has two parts
  - The first part binds names to values
  - The second part uses the names defined in the first part
- In Scheme:

```
(LET (
   (name1 expression1)
   …
   (namen expressionn)
)
```

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The `LET` Construct (continued)

- In ML:

```
let
  val name1 = expression1
  …
  val namen = expressionn
in
 expression
end;
```

- In F#:
  - First part: `let` left_side = expression
  - (left_side is either a name or a tuple pattern)
  - All that follows is the second part

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Declaration Order

- In older C (C89), all variable declarations in a function (except inside nested blocks) had to appear **at the beginning** of the function

```
void foo() {
   int x;
   int y;   // all declarations first
  x = 5;   // statements only after
}
```

```
for (int i = 0; i < 5; i++) // not allow in C89
```

- C99, C++, Java, and C# allow variable declarations to appear anywhere a statement can appear
-

```
for (int i = 0; i < 5; i++) // legal in C99
```

  - In C99, C++, and Java, the scope of all local variables is from the declaration to the end of the block
  - In the official documentation of C#, the scope of any variable declared in a block is the whole block, regardless of the position of the declaration in the block
    - However, that is misleading, because a variable still must be declared before it can be used

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Declaration Order (continued)

- In C++, Java, and C#, variables can be declared in `for` statements
  - The scope of such variables is restricted to the `for` construct

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Global scope

- Some languages (C, C++, PHP, JavaScript, Python) allow variables to be defined **outside any function.** These are **global variables** and may be visible inside functions depending on the language's rules.

- C and C++ distinguish between **declarations** and **definitions** of global variables: **Declarations** describe type and attributes but do not allocate storage. **Definitions** allocate storage

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Global scope

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- C and C++ distinguish between **declarations** and **definitions** of global variables: **Declarations** describe type and attributes but do not allocate storage. **Definitions** allocate storage

- **Declaration** `extern int count;  // declaration only`
- **Definition** `count = 0;  // create a variable and allocates memory`

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Global scope (example)

hello.c
```
Int x =10;
```

hello.h
```
extern int x;
```

luis.c
```
#include “hello.h”
x=x+5;
printf(“x=%d\n”,x); /prints 15, update global
```

---

hello.c
```
#include <stdio.h>

void greet() {     // Definition
   printf("Hello!\n");
}
```

hello.h
```
void greet() or extern void greet()
```

luis.c
```
#include “hello.c”

greet();
```

Extern in functions

hello.c
```
add(int a, int b) {
      return a + b;
}
```

hello.h
```
extern add(int a, int b)
```

luis.c
```
#include “hello.h

int main() {
int x = add(3,4);
```

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Global scope python

- Python allows globals to be **referenced** inside a function, but to **assign** to a global variable inside a function, it must be declared global in that function. Otherwise, the assignment creates a **new local variable**, which makes earlier references illegal

```
day = "Monday"

def tester():
    global day
    print(day)      # OK
    day = "Tuesday" # modifies global

tester()
print(day)  # Tuesday
```

```
Monday
Tuesday
```

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Global Scope (continued)

- PHP
  - Programs are embedded in HTML markup documents, in any number of fragments, some statements and some function definitions
  - The scope of a variable (implicitly) declared in a function is local to the function
  - The scope of a variable implicitly declared outside functions is from the declaration to the end of the program, but skips over any intervening functions
    - Global variables can be accessed in a function through the `$GLOBALS` array or by declaring it `global`

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```php
<?php
$greeting = "Hello";   // Global variable (outside any function)
?>

<p>Before function call</p>

<?php
function sayHello() {
    $name = "Luis";   // Local variable (only inside function)

    // Access global using GLOBAL keyword
    global $greeting;
    echo "$greeting $name (using global)<br>";

    // Access global using $GLOBALS array
    echo $GLOBALS['greeting'] . " again $name (using GLOBALS)<br>";
}
?>

<p>Calling function...</p>

<?php
sayHello();
?>

<p>After function call</p>

<?php
echo "Outside function, greeting is still: $greeting<br>";
?>

<p>Calling function...</p>

<?php
sayHello();
?>

<p>After function call</p>

<?php
echo "Outside function, greeting is still: $greeting<br>";
?>

</body>
</html>
```

```
PHP Scope Example

Before function call

Calling function...
Hello Luis (using global)
Hello again Luis (using GLOBALS)

After function call
Outside function, greeting is still: Hello
```

Global Scope (continued)

- Python
  - A global variable can be referenced in functions, but can be assigned in a function only if it has been declared to be `global` in the function

- count = 10 # Global variable. Which function will work

```
def show():
    # Referencing global variable (reading only)
    print("Count is:", count)
```

```
def increment_one():
    # Trying to assign without declaring global
    count = count + 1
```

```
def increment_two():
    global count count = count + 1
```

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Evaluation of Static Scoping

- Works well in many situations
- Problems: (make everything global to avoid over thinking)
  - In most cases, too much access is possible
  - As a program evolves, the initial structure is destroyed and local variables often become global; subprograms also gravitate toward become global, rather than nested

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Dynamic Scope

- Based on calling sequences of program units, not their textual layout (temporal versus spatial)
- References to variables are connected to declarations by searching back through the chain of subprogram calls that forced execution to this point

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Scope Example

```
function big() {

    function sub1() {
        var x = 7;
    }

    function sub2() {
        var y = x;
        console.log(y);
    }

    var x = 3;

    sub1();
    sub2();
}

big();
```

Static scoping
- » Y=3

Dynamic scoping
- » Y=3

```
function big() {

    function sub1() {
        var x = 7;
        sub2();           // sub1 calls sub2
    }

    function sub2() {
        var y = x;
        print(y);
    }

    var x = 3;

    sub1();
}

big();
```

Static scoping
Y=3
Dynamic scoping
Y=7

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Scope Example

- Evaluation of Dynamic Scoping:
  - Advantage: convenience
  - *Disadvantages:*
    1. While a subprogram is executing, its variables are visible to all subprograms it calls
    2. Impossible to statically type check
    3. Poor readability– it is not possible to statically determine the type of a variable

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Scope and Lifetime

- Scope and lifetime are sometimes closely related, but are different concepts
- Consider a `static` variable in a C or C++ function

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Example (scope and lifetime)

```c
#include <stdio.h>

void counter() {
    static int count = 0;  // static local variable
    count++;
    printf("count = %d\n", count);
}

int main() {
    counter();
    counter();
    counter();
    return 0;
}
```

```
count = 1
count = 2
count = 3
```

```c
void counter() {
    static int count = 0;
}

int main() {
    printf("%d", count);
}
```

?

Lifetime?

What is static scope?

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Referencing Environments

- The *referencing environment* of a statement is the collection of all names that are visible in the statement
- In a static-scoped language, it is the local variables plus all of the visible variables in all of the enclosing scopes
- A subprogram is active if its execution has begun but has not yet terminated
- In a dynamic-scoped language, the referencing environment is the local variables plus all visible variables in all active subprograms

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Examples: *referencing environment* print(x + y)

```python
x = 1

def outer():
    y = 2
    def inner():
        print(x + y)
```

At the line `print(x + y)`, the referencing environment is:

Scope Level	Names Visible
Local to `inner`	(none declared here)
Enclosing (`outer`)	`y`
Global	`x`
Built-in	`print`, etc.

```javascript
function A() {
    x = 5
    B()
}

function B() {
    y = 10
    C()
}

function C() {
    print(x + y)
}
```

`C → B → A`

So the referencing environment includes:

From	Variables
C (local)	none
B (caller)	y
A (caller's caller)	x

So again `{x, y}` — **but only because of the call chain**, not because of code nesting.

If `C()` were called directly from `main`, `x` or `y` might be missing.

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Named Constants

- A *named constant* is a variable that is bound to a value only when it is bound to storage
- Advantages: readability and modifiability
- Used to parameterize programs
- The binding of values to named constants can be either static (called *manifest constants*) or dynamic
- Languages:
  - C++ and Java: expressions of any kind, dynamically bound
  - C# has two kinds, `readonly` and `const`
    - the values of `const` named constants are bound at compile time
    - The values of `readonly` named constants are dynamically bound

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Named Constants

- const double PI = 3.14159;
- area = PI * r * r;
- const double INTEREST_RATE = 0.08;
- double interest = balance * INTEREST_RATE;

Static binding

```
const int SIZE = 10;
int arr[SIZE]; //SIZE must be known at compile time
```

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Name constants

- const int x = rand(); // Value determined at runtime (dynamic binding)
  Still constant but not known during compilation.

```
const int a = 5;          // compile-time constant
const int b = f();        // runtime constant

final int x = 10;         // compile-time constant if literal
final int y = getValue(); // runtime constant
```

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Summary

- Case sensitivity and the relationship of names to special words represent design issues of names
- Variables are characterized by the sextuples: name, address, value, type, lifetime, scope
- Binding is the association of attributes with program entities
- Scalar variables are categorized as: static, stack dynamic, explicit heap dynamic, implicit heap dynamic
- Strong typing means detecting all type errors

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